a solid is determined by the nature of the atoms composing the physical molecules, and is not a measure of the thermal work done in expansion.

The paper concludes with a discussion of the relations of specific heat to atomic weight in the solid, liquid and gaseous states.

"Further Researches on the Temperature Classification of Stars."

By Sir NORMAN LOCKYER, K.C.B., LL.D., F.R.S. Received January 30,—Read February 18, 1904.

[PLATES 7—9.]

CONTENTS.

1. *Historical Review.*

In my first Bakerian Lecture in 1873 I dealt with the question of the spectra of stars, and pointed out that the facts accumulated up to that time by Rutherford and others led to the view that in the reversing layers of the sun and stars various degrees of dissociation are at work.

I also suggested that the stellar evidence indicated that one of the results of dissociation temperatures could be to "prevent the coming together of atoms which at the temperature of the earth, and at all artificial temperatures yet obtained here, compose the metals, the metalloids, and compounds."*

In a subsequent communication to the Paris Academy I wrote,† "Il semble que plus une étoile est chaude plus son spectre est simple, et que les éléments métalliques se font voir dans l'ordre de leurs poids atomiques."

This last generalisation rested upon the great preponderance of hydrogen in certain stars, which I classed as hottest on the ground that the blue end of the spectrum was open. Of the spectrum of helium,

* 'Phil. Trans.,' vol. 164, p. 479.

† 'Comptes Rendus,' vol. 77, 1873, p. 1357.

which I had first observed and named in 1869, we then knew nothing either on the earth or in the stars; the solar line D_3 being its only representative. The question of the relative temperatures of stars became of great importance in relation to the questions thus raised, but it was not till 1892 that I was able to approach it by means of photography. The interval was spent chiefly in researches bearing upon solar and terrestrial changes in spectra when differences of thermal and electric energies were obvious.

In a paper on stellar spectra in relation to temperature, communicated to the Royal Society in 1902,* I gave an account of an attempt at a temperature classification of stars, utilising the fact that an extension of spectra into the ultra-violet is produced by increased temperature, and further that a lower temperature in an atmosphere above a photosphere would increase the absorption in the blue end. The classification arrived at was based on photographs obtained with instruments having prisms and lenses made of glass which has a strong absorbing effect on the ultra-violet rays.

The general results of the discussion was the conclusion that the stars so far considered might be divided into two series, one of ascending, the other of descending temperature. Further, that the classification proposed was justified both by the relative extensions of the spectra into the ultra-violet and by the temperature sequence of the few typical lines then available for study.

By 1899, laboratory work on the spectra of different substances under different conditions, and the discovery of a terrestrial source of helium by Ramsay, which enabled me to investigate the complete spectrum, had so far facilitated the study of the typical lines in the various stellar spectra, that I felt myself justified in attempting to classify the stars in relation to the chemical sequence revealed by the presence of gaseous and metallic lines, using especially the lines of helium and hydrogen and the "enhanced" and arc lines of the metals. In this way I hoped to be able to test the classification of 1892 based on the relative lengths of spectra.

An account of this research was published in the Proceedings of the Royal Society (vol. 65, pp. 186—191, 1899), and ultimately the complete results obtained were included in a "Catalogue of 470 Brighter Stars Classified According to their Chemistry."†

In this catalogue the stars were arranged in sixteen groups along a temperature curve with its apex in the central portion. On the assumption that the chemical changes were due to temperature, including in that term the possible results of electrical energy, the general arrangement of the stellar groups in the order both of ascending and descending temperatures was indicated, the group

* 'Phil. Trans.,' A, vol. 184, p. 688.

† 'Publications of the Committee on Solar Physics,' London, 1902.

containing the hottest stars, on the dissociation hypothesis, being placed at the top of the curve. It will be convenient to reproduce this table here.

10		Argonian	
9		Alnitamian	
		Protohydrogen Stars	
8	Crucian	Cleveite-gas Stars	Achernian
7	Taurian		Algolian
6	Rigelian	Proto-metallic Stars	Markabian
5	Cygnian		—
4	—		Sirian
3	Polarian		Procyonian
2	Aldebarian	Metallic Stars	Arcturian
1	Antarian	Stars with fluted spectra	Piscian

There was abundant chemical evidence to show that the mean temperature of the stars occupying the same height on both branches of the curve was not very different, so that we have ten horizons, or stages, of mean temperature indicated in passing from the complete fluted spectra of Antarian-Piscian stars to the simplified line spectra of the γ Argus type.

So far as we could judge from the photographs then available, the chemical changes gave a sequence identical with that desired for the length of ultra-violet spectra in 1892, so that the latter classification was fully justified by the test which had been applied to it.

2. *Aims and Conditions of the Present Research.*

As before mentioned in the work of 1892, the relative lengths of the ultra-violet spectra were determined from photographs secured with instruments having glass optical parts. It was possible therefore to secure still another test by obtaining a new set of photographs using calcite and quartz in place of glass, to enable the far ultra-violet to be obtained and studied. Nor was this all, it seemed of the first importance to utilise not only the length of spectrum in the blue, but the relative brightness of the different parts. What happens regarding the relative brilliancy of the different parts of the spectrum, as well as the extension into the ultra-violet by increased temperature, was very

clearly stated by Sir George Stokes* in 1876, in the following words, "When a solid body such as a platinum wire, traversed by a voltaic current, is heated to incandescence, we know that as the temperature increases, not only does the radiation of each particular refrangibility absolutely increase, but the proportion of the radiations of the different refrangibilities is changed, the proportion of the higher to the lower increasing with the temperature."

This question was also investigated by Melloni and Crova; and in recent years exact determinations of the law of increase have been made by Lummer, Paschen, and others. Melloni showed† experimentally that the maximum radiation moved towards the more refrangible end of the spectrum as the temperature increased. Crova made use of this fact in determining the temperatures of various incandescent light sources, and was one of the first to suggest‡ that the method was applicable to the determination of the temperatures of the sun and stars.

3. *The Observational Conditions.*

The kind of spectroscope to be used and method of observation to be followed were indicated by the following considerations.

In order to utilise the effect of temperature changes to the full it was necessary to record the red end of the spectrum as well as the ultra-violet, as only in this way could the *relative* changes in intensity be recorded, *hence it was desirable to employ only a small dispersion.*

In addition to the natural differences photographed in the ultra-violet, artificial differences due to the absorbing effect of our atmosphere—which, even when clearest, is more or less opaque to the ultra-violet radiations—might be introduced, therefore it was considered advisable, in order to eliminate the effects of atmospheric absorption, to obtain the spectra of any two stars to be compared *whilst they were at approximately the same altitude.* Further, to avoid the many pit-falls to which those who compare photographs taken on plates of unequal sensitiveness, and differently exposed and developed, are liable, it was obviously important that any spectra to be compared should be obtained on the same plate in order to secure identical plate sensitiveness and development.

Again, in order to secure similar optical treatment it was arranged to photograph both spectra near to the optical axis of the camera; thus they are near together in the centre of the plate.

I am sorry to say this work has been considerably delayed by the long time taken in preparing a new camera and optical parts suitable for the research, as above defined, and latterly by a long spell of bad observing weather.

* 'Roy. Soc. Proc.,' vol. 24, p. 353, 1876.

† Taylor's 'Scientific Memoirs,' vol. 1, p. 56.

‡ 'Comptes Rendus,' vol. 87, p. 981.

4. *Description of the Instrument used.*

With regard to the new apparatus, I may state that an objective prism camera (fig. 1), was devised having a 2-inch 30° calcite prism mounted in front of a $2\frac{1}{2}$-inch quartz lens of 18 inches focal length.

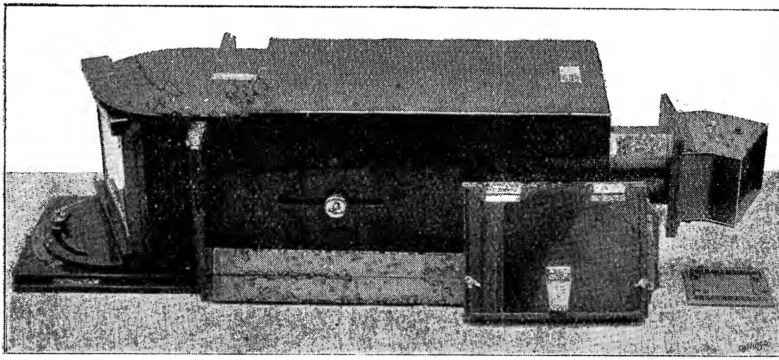


FIG. 1.—Quartz-Calcite Prismatic Camera.

The prism is so cut that its first face is perpendicular to the optic axis of the crystal, and it is arranged that the incident rays are normal to this face. All the rays, therefore, pass through the prism parallel to the optic axis and in this way there is no double refraction.

The whole length of the spectrum is brought into focus in a plane inclined at 42° to the optical axis. The apparatus is attached to the side of an equatorially mounted 6-inch Dallmeyer doublet camera with an angle in declination between the two optical axes equal to the angle of deviation of the calcite prism, so that the Dallmeyer is used as a finder.

Edward's snap-shot isochromatic plates have alone been used, and as they are not sufficiently sensitive for wave-lengths between λ 486 and λ 550 (approx.), there is a break in each spectrum about this region followed by a further portion of the spectrum having its centre about "D." The length of spectrum obtained is such that H_β to H_ϵ is 0·355 inch (9·0 mm.) and from H_ϵ to H_γ 0·165 inch (4·2 mm.).

5. *Method of Work.*

As shown in Table I, there are ten stages or steps of temperature to be investigated, and pairs of stars were selected in order to show the differences between adjacent stages or else the difference between stages widely apart.

Stages 1 and 10 are not available in consequence of the photographic faintness of the Antarian and Piscian stars, and the fact that the only

star as yet known representing the Argonian group is situated in the Southern Hemisphere. The stages already investigated are shown by brackets in the following table.

Table I.

10.		Argonian.	
9.		Alnitamian.	
8.	Crucian.	Achernian.	3.
7.	Taurian.	Algolian.	
6.	Rigelian.	Markabian.	5. 7.
5.	Cygnian.	———	2. 6.
4.	———	Sirian.	4.
3.	Polarian.	Procyonian.	1.
2.	Aldebarian.	Arcturian.	
1.	Antarian.	Piscian.	

Thus an Arcturian star (second stage), was compared with a Sirian (fourth stage), and so on. In the case of some stars, *e.g.*, Capella, this was repeated several times, each photograph showing a different comparison.

In securing the photographs an attempt was always made to obtain the pair of spectra with the region between H_β and H_γ of the same intensity in each. This condition is very difficult to fulfil in actual practice owing to the difference of magnitude of the two stars, their difference in declination, and hence in clock rate, and lastly the very important actual differences between the actinism of the two bodies in this region of the spectrum due to their different temperature conditions.

It was also arranged to obtain, whenever possible, the spectra of two stars near together, so that the chances of introducing atmospheric interference due to the different conditions possibly present in various parts of the sky might be reduced to a minimum. In every case where the observer had reason to suspect any change in the atmospheric conditions obtaining during the two exposures, which sometimes extended over a period of $1\frac{1}{2}$ hours, the result has not been included in the discussion.

Thus we have a series of comparison photographs from which all variable conditions except the natural variations in radiation have, as far as possible, been eliminated.

6. *Description of the Photographs.*

Many of the photographs taken are too faint to reproduce well enough to exhibit completely the striking differences shown between the pairs of spectra. I shall therefore content myself by giving a detailed description of each negative (Table II), only reproducing those photographs which are sufficiently dense to plainly show the phenomena under discussion.

Table II.

No. of negative.	Date.	Star.	Stage of temperature.	Type.	Altitude.	Description.
		From Stage 2 to Stage 4.				
19	7.5.03	α Lyræ	4	Sir.	56°	Faintly red, fairly bright to Hγ.
		α Boötis	2	Arct.	57	Intense red, scarcely extends beyond K.
4	29.12.02	β Ursæ Maj.	4	Sir.	59	Red scarcely visible, maximum about λ 400.
		α Ursæ Maj.	2	Arct.	58	Fairly bright red, maximum about λ 460.
14	17.2.03	α Geminorum	4	Sir.	42	Red scarcely visible, maximum about λ 418.
		α Aurigæ	2	Arct.	39	Fairly bright red, maximum about λ 455.
37	21.1.04	α Geminorum	4	Sir.	68	Weak red, maximum about λ 420.
		α Aurigæ	2	Arct.	68	Very dense red; blue maximum commences at F, centre at λ 460, weak beyond λ 388.
		From Stage 4 to Stage 6.				
11	28.1.03	β Orionis	6	Rig.	21	Red not so intense, and ultra-violet much more extended than in Sirius.
		α Canis Maj.	4	Sir.	22	Dense red, centre of maximum about λ 422.

Table II—*continued.*

No. of negative.	Date.	Star.	Stage of temperature.	Type.	Altitude.	Description.
		From Stage 6 to Stage 9.				
35		κ Orionis	9	Alnit.	20°	Although spectrum of Rigel is generally much stronger, that of Alnitam extends as far into the ultra-violet.
		β Orionis	6	Rig.	24	
		Various Intervals.				
34	10.12.03	γ Ursæ Maj.	6	Mark.	78	Faint red, maximum about λ 416, well sustained up to Hθ.
		α Ursæ Maj.	2	Arct.	76	Fairly bright red, maximum at λ 460, rapidly falling off beyond λ 430.
36	14.1.04	η Ursæ Maj.	8	Cruc.	51	Faint red, maximum at about λ 418, bright extension well beyond the end of the Capella spectrum.
		α Aurigæ	2	Arct.	52	Very bright red, maximum at about λ 455, faint beyond K.
23	14.11.03	ε Orionis	9	Alnit.	38	Faint red, centre of maximum at about Hδ. Bright extension far beyond the hydrogen series.
		α Canis Min.	3	Proc.	41	Very bright red, maximum about Hγ, and falls quickly beyond Hκ.
		Extreme Interval.				
33	10.12.03	ε Orionis	9	Alnit.	36	Very faint red, centre of maximum about Hδ, *i.e.*, near the more refrangible end of the Aldebarian spectrum.
		α Tauri	2	Aldeb.	36	Very strong red, centre of maximum about λ 465, end of spectrum about Hδ.

7. *Discussion of Photographs.*

The following is a detailed discussion of the photographs described in Table II.

Stage 2 *to Stage* 4.

No 19. This photograph of Vega (fourth stage), and Arcturus (second stage), is very striking in the relative intensities of the two spectra. The red portion of the Arcturian spectrum is considerably more intense and forms the one end of a maximum which—except in the green region where the plate is not very sensitive—extends from D to about λ 454. The part of the spectrum more refrangible than that rapidly becomes less intense, until at and beyond K it is very faint. Matters are very different in the spectrum of Vega. Here the maximum radiation occurs about a third of the distance from H_δ to H_γ (λ 422) and the spectrum extends without any great falling off in intensity to H_ν, beyond that it is weaker but continues without any great decrease to twice the distance on the more refrangible side of H_ν than the latter is from K. From that point to the end the spectrum gradually declines. Whilst the maximum radiation in this spectrum has moved wholesale towards the ultra-violet, the red is relatively only about half the density of the red in the Arcturian spectrum.

No. 4. The general appearance of these two spectra leads to the conclusion that that of β Ursæ Majoris (fourth stage) is much stronger than that of α Ursæ Majoris (second stage).

A more careful examination, however, shows that whilst the detached red part of the former is only seen with difficulty, the same portion of the latter is comparatively prominent.

The maximum intensity in α is situated at about λ 450 and does not vary a great deal between there and K. After the latter point is reached, however, the fall is rather sudden, and the spectrum soon dies out. In β the maximum intensity is between H and H_ϵ, and the ultra-violet up to H_κ is fairly strong. Beyond H_κ the intensity of the spectrum drops rather suddenly, and then continues with a gradual decrease for some distance.

No. 14. There is no great difference in the lengths of these two spectra, the one of α Geminorum (fourth stage), the other α Aurigæ (second stage), but the red portion of the second stage spectrum is most decidedly more intense than that of the fourth stage, the latter, in fact, being scarcely visible at all. In α Aurigæ the maximum intensity is at about λ 454, but in α Geminorum it must be placed at or near to H_δ (λ 410).

No. 37. In the taking of this negative the spectrum of Capella (second stage) received the advantage of exposure and is consequently much stronger in the H_γ—H_β region than that of Castor (fourth

stage), and yet the latter extends as far into the ultra-violet as the former.

Furthermore, the intensity of the blue part of the spectrum of Capella rises to its maximum immediately at H_β and commences to decline towards the violet at H_γ, whereas the maximum region of Castor does not commence at once after leaving the green gap, and attains its centre at about λ 422.

It will be observed that whether we take Arcturus or Capella to represent Stage 2, the spectra of stars of higher stages have relatively longer ultra-violet and reduced red radiation. It has to be noted, however, that there are indications that Stage 2 will, as a result of further work, have to be divided, for Capella is certainly hotter than Arcturus as determined in the manner now under discussion.

Stage 4 *to Stage* 6.

No. 11. On examination of this negative it is seen that the detached red portion of the spectrum of Sirius (fourth stage) is decidedly more intense than the same portion of the Rigelian spectrum (sixth stage). In the ultra-violet, however, we find that although both stars are fairly high on the temperature curve, and, therefore, both spectra extend far into the ultra-violet, the extension of the spectrum of Rigel is more intense and greater than that of Sirius.

Stage 6 *to Stage* 9.

No. 35. By reason of its greater exposure the spectrum of Rigel (sixth stage) is generally much stronger than that of κ Orionis (ninth stage), and especially is this so in the red portions of the two spectra. This inequality notwithstanding, the spectrum of κ extends practically as far into the ultra-violet as that of Rigel.

Various Intervals.

No. 34. In α Ursæ (second stage) the red part of the spectrum is comparatively very bright, nearly as bright as the region between G and F. In γ Ursæ (sixth stage) this red portion is barely visible. Again, in the α Ursæ spectrum the maximum occurs at λ 460, and then the intensity gradually declines to K, beyond which it is very faint. The maximum intensity of the γ Ursæ spectrum is situated at about λ 422, and it extends without becoming greatly impaired to H_θ.

No. 36. In this comparison we have a very striking case. The spectrum of Capella (second stage) is compared with that of η Ursæ Majoris (eighth stage); Capella has been over-exposed, so that the red portion is abnormally intense, η Ursæ Majoris received the correct exposure, and the red part of the spectrum is rather faint.

Notwithstanding this difference the spectrum of η Ursæ extends further into the ultra-violet than does that of Capella, and not only does it extend further, but the maximum intensity is extended much further into the ultra-violet than is that of Capella, which drops off rapidly beyond K.

No. 23. In this comparison the red part of the Procyon (third stage) spectrum is much brighter than that of Alnitam (ninth stage). The intensity in the longer portion of the spectrum of Procyon rises at once to its maximum at H_β, has its centre of maximum at about λ 460, and at H_γ commences to diminish towards the violet. In the spectrum of Alnitam, however, the maximum is delayed until the region about λ 426 is reached, and is then sustained up to H_ζ, finally extending to the ultra-violet with a marked superiority, comparatively, over that of the Procyon spectrum.

Extreme Interval.

No. 33. This comparison of two type stars respectively situated near the extremities of the temperature curve is naturally one of the most striking pieces of evidence in support of this method of temperature classification. The spectrum of Alnitam (ninth stage) is nowhere so intense as the red and blue parts of the Aldebaran (second stage) spectrum, and yet it extends more than twice as far towards the ultra-violet, from H_β, as the hydrogen series, whilst the more refrangible limit of the Aldebaran spectrum only extends to K. The maximum intensity of the blue portion of the Alnitam spectrum occurs much nearer the ultra-violet than that of the Aldebaran spectrum, the latter attaining its maximum at about λ 465.

8. *Conclusions.*

It may be pointed out that the temperature classification, confirmed by this research, does not agree with that published by Sir William and Lady Huggins who, in their "Atlas of Representative Stellar Spectra" containing "a Discussion of the Evolutional Order of the Stars," place the solar stars on a higher temperature level than the white stars.

A reduction of intensity in the continuous spectrum beyond the hydrogen series to which attention has been called by more than one observer, Schumann* among others, does not affect the results which I have stated. Another paper dealing with this and similar points is in course of preparation.

The result of the research may be stated as follows :—

Taking the stars assumed to be hottest in the chemical classification, we find that in all cases the relative length of the spectrum is reduced,

* 'Smithsonian Contributions to Knowledge,' No. 1413, 1903, p. 23.

and the relative intensity of the red is increased, as a lower temperature is reached. That is to say that where two spectra having their intensities about the region H_β — H_γ equal are compared, we find that in the cooler stars, according to the chemical classification, the emissions in the red preponderate, whilst in the hotter star the ultra-violet is more extended and intense.

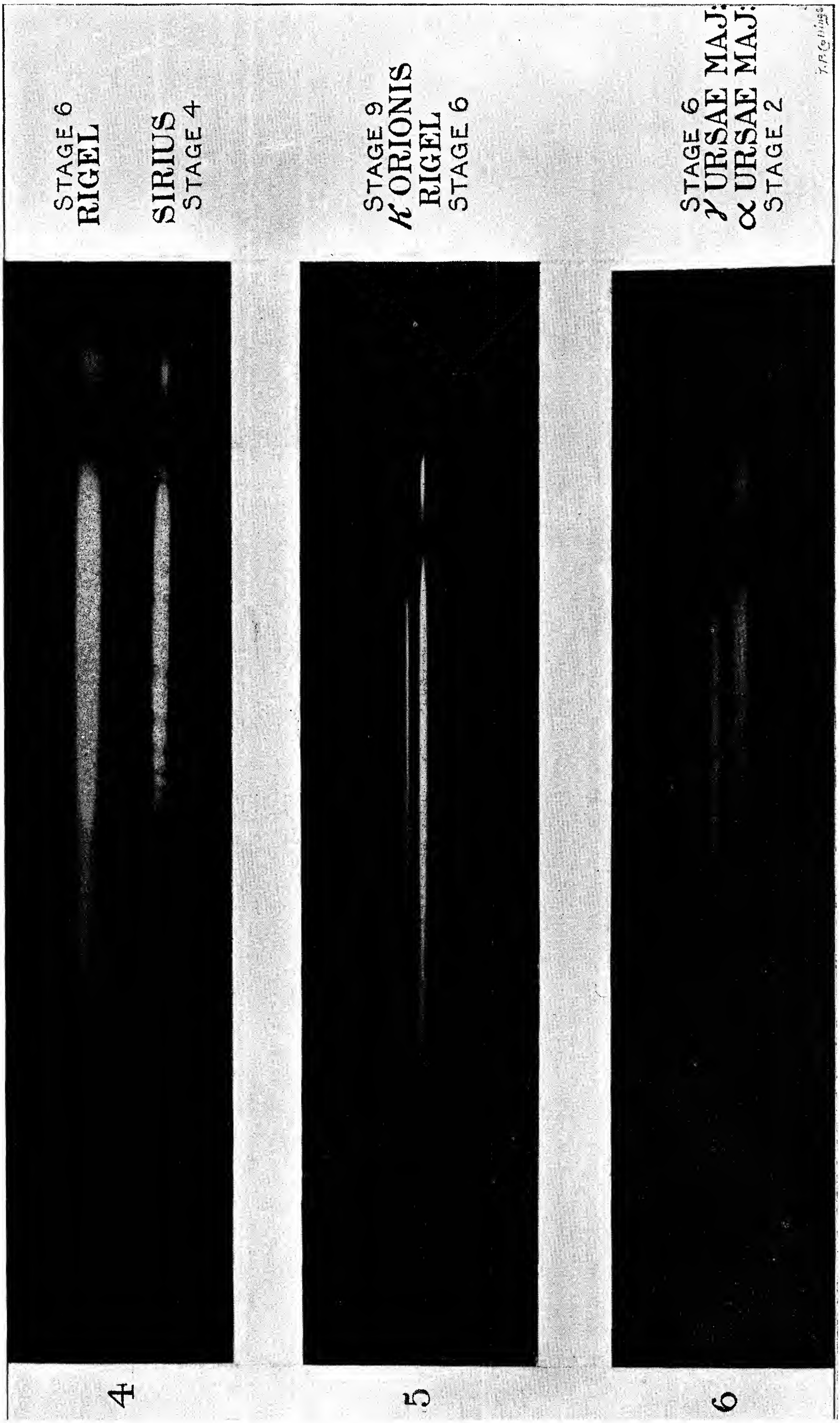
My best thanks are due to Messrs. Rolston and Goodson, who took the various photographs to which I have referred, the former also helping me in the preparation of this paper, and to Mr. Wilkie for preparing the enlargements of the negatives.

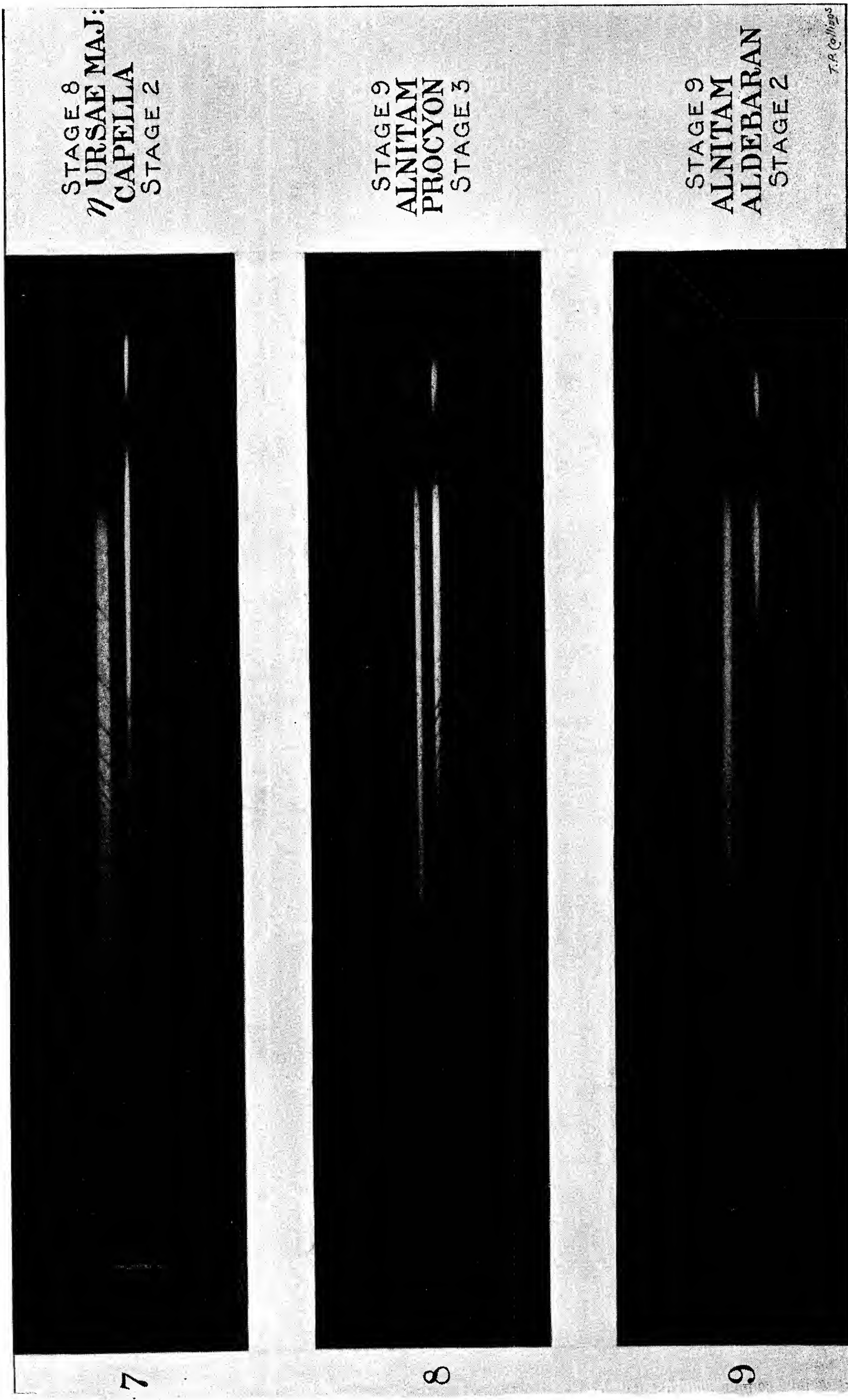
9. *Description of Plates.*

No.	No. of negative.	Stars.	Stage.	Type.
		Plate 7.		
1	19	Vega .... Arcturus	4 2	Sir. Arct.
2	14	Castor........ Capella	4 2	Sir. Arct.
3	37	Castor........ Capella.......	4 2	Sir. Arct.
		Plate 8.		
4	11	Rigel .... Sirius	6 4	Rig. Sir.
5	35	κ Orionis...... Rigel.........	9 6	Alnit. Rig.
6	34	γ Ursæ Maj. .. α Ursæ Maj. ..	6 2	Mark. Arct.
		Plate 9.		
7	36	η Ursæ Maj. .. Capella.	8 2	Cruc. Arct.
8	23	Alnitam ...... Procyon	9 3	Alnit. Proc.
9	33	Alnitam ...... Aldebaran	9 2	Alnit. Aldeb.

In producing these plates the original negatives have been enlarged about $3\frac{1}{2}$ times.


STAGE 4
VEGA
ARCTURUS
STAGE 2
STAGE 4
CASTOR
CAPELLA
STAGE 2
STAGE 4
CASTOR
CAPELLA
STAGE 2
1
2
3


STAGE 6
RIGEL
SIRIUS
STAGE 4
4
STAGE 9
κ ORIONIS
RIGEL
STAGE 6
5
STAGE 6
γ URSAE MAJ:
α URSAE MAJ:
STAGE 2
6


STAGE 8
η URSAE MAJ:
CAPELLA
STAGE 2
7
STAGE 9
ALNITAM
PROCYON
STAGE 3
8
STAGE 9
ALNITAM
ALDEBARAN
STAGE 2
9

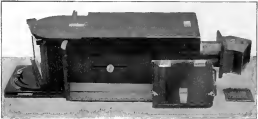


FIG. 1.—Quartz-Calcite Prismatic Camera.

1 

STAGE 4
VEGA
ARCTURUS
STAGE 2

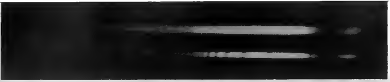
2 

STAGE 4
CASTOR
CAPELLA
STAGE 2

3 

STAGE 4
CASTOR
CAPELLA
STAGE 2

T.P. Collings

4

STAGE 6
RIGEL

SIRIUS
STAGE 4

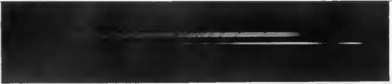
5

STAGE 9
κ ORIONIS
RIGEL
STAGE 6

6

STAGE 6
γ URSAE MAJ:
α URSAE MAJ:
STAGE 2

7

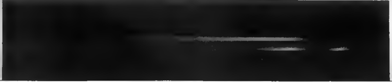


STAGE 8
η URSAE MAJ;
CAPELLA
STAGE 2

8

STAGE 9
ALNITAM
PROCYON
STAGE 3

9



STAGE 9
ALNITAM
ALDEBARAN
STAGE 2